



Fermi National Accelerator Laboratory

FERMILAB-Pub-99/209-T

**New Backgrounds in Trilepton, Dilepton and Dilepton Plus Tau Jet
SUSY Signals at the Tevatron**

Konstantin T. Matchev

*Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510*

Damien M. Pierce

*Brookhaven National Laboratory
Upton, New York 11973*

September 1999

Submitted to *Physics Letters B*

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Distribution

Approved for public release; further dissemination unlimited.

Copyright Notification

This manuscript has been authored by Universities Research Association, Inc. under contract No. DE-AC02-76CH03000 with the U.S. Department of Energy. The United States Government and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government Purposes.

New backgrounds in Trilepton, Dilepton and Dilepton plus Tau Jet SUSY Signals at the Tevatron

KONSTANTIN T. MATCHEV

Theoretical Physics Department
Fermi National Accelerator Laboratory
Batavia, IL 60510

DAMIEN M. PIERCE

Physics Department
Brookhaven National Laboratory
Upton, NY 11973

Abstract

We determine the Tevatron's reach in supersymmetric parameter space in trilepton, like-sign dilepton, and dilepton plus tau-jet channels, taking all relevant backgrounds into account. We show results for the minimal supergravity model. With a standard set of cuts we find that the previously unaccounted for $W\gamma^*$ background is larger than all other backgrounds combined. We include cuts on the dilepton invariant mass and the W -boson transverse mass to reduce the $W\gamma^*$ background to a reasonable level. We optimize cuts at each point in supersymmetry parameter space in order to maximize signal-to-noise.

Submitted to Phys. Lett. B

1 Introduction

Low-energy supersymmetry (SUSY) is the most popular extension of the Standard Model (SM). It is vigorously sought at LEP, and has been and will continue to be actively looked for in the previous and forthcoming runs of the Fermilab Tevatron Collider [1].

There are many possible manifestations of low-energy SUSY. With more than 100 new parameters, theorists have out of necessity invented high scale models with drastically fewer parameters. These models can have qualitatively distinct low-energy spectra, leading to a variety of collider signatures. In this paper we explore the reach of the Tevatron in the parameter space of the most commonly considered model, the minimal supergravity model [2]. As in many models, this model respects gaugino mass unification. This implies that in the physical low-energy spectrum the electroweak gauginos are significantly lighter than the gluino, so that their production cross sections are the largest in the allowed regions of parameter space. In addition to a large production cross section we want a significant branching fraction into a channel with relatively small Standard Model background. With all this in mind, the trilepton (3L) signal, $\ell^\pm \ell^+ \ell^- \cancel{E}_T$ with $\ell = e$ or μ , has been considered a gold-plated mode for SUSY discovery at the Tevatron [3, 4, 5, 6, 7, 8, 9], prompting several Run I analyses at the Tevatron [10]. The 3L signal is mainly produced via $p\bar{p} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^+$. Being one of the most extensively studied channels for SUSY discovery, it was naturally among the main focal points of the Run II Workshop [1], where the emphasis was placed on optimizing the analysis cuts in order to maximize the Run II Tevatron reach.

In a recent paper [8], we took this approach further by considering thousands of sets of cuts in order to determine which one gives the best reach. We also supplemented our trilepton SUSY search with two other promising signatures — the inclusive like-sign dilepton [11] and ‘dilepton plus a tau jet’ [7] channels. Along with the mandatory plots of the Tevatron reach in parameter space, the main result from [8] was that the SM background has been grossly underestimated in the previous studies ([4, 6], and to some extent in [5]). We traced the main cause of the problem to the inadequacy of the event generator ISAJET [12] in simulating the

SM WZ and ZZ backgrounds. In ISAJET the zero width approximation is used in generating both WZ and ZZ . In PYTHIA [13], a Breit-Wigner distribution is used for the W - and Z -bosons. The finite Z -width leads to broader dilepton spectra and hence significantly larger background.

The $W\gamma^*$ background is not incorporated in either ISAJET or PYTHIA. Hence, it has not been taken into account in previous studies (see, however, Refs. [14, 9]). We find that this background is larger than all previously considered backgrounds combined. In light of the importance of the trilepton channel for Run II, we are compelled to update our analysis of Ref. [8].

We were faced with several options as to how to incorporate the $W\gamma^*$ process*. There are several parton level Monte Carlo generators which use the full set of diagrams (see Fig. 1) to generate what is loosely called “ WZ ”, but in reality is the $2 \rightarrow 4$ process $p\bar{p} \rightarrow \ell^\pm \nu \ell'^+ \ell'^-$. Three such generators are MADGRAPH [15], COMPHEP [16] and MCFM [14]. The choice of a particular generator is dictated by a matter of convenience and/or experience. We want to not only generate WZ events with the correct kinematics, but also to include a full detector simulation as we did in [8], making use of the SHW package [17, 18, 19]. In addition, to make the simulation fully realistic, we need to include the effects from initial and final state radiation (ISR,FSR), therefore we cannot just link one of the leading order parton level Monte Carlos to our detector simulation package. What we choose to do instead is to use COMPHEP to generate hard scattering events at leading order, then we pipe those through PYTHIA which adds showering and hadronization, and finally we run the result through SHW[†]. The resulting parton-level cross section was integrated with the CTEQ4m structure functions [21].

Unfortunately, with a standard set of cuts [6] the $W\gamma^*$ background is about 2.7 fb, which

By $W\gamma^$ we implicitly refer to the $Z\text{-}\gamma^*$ interference as well.

[†]Alternatively, one can omit the first step and generate the WZ events directly from PYTHIA, reweighting the events so as to fit the distributions of a few key variables (e.g. dilepton invariant mass, lepton p_T spectrum or angular distributions, etc.). In the early stages of this project we followed this approach and reweighted the PYTHIA events to fit the invariant mass distribution from MCFM. We then applied the same cut optimization procedure as in [8], and presented our results for the Tevatron reach in a series of talks [20]. This procedure is, of course, only an attempt to approximate what we are doing here. The results turn out to be in reasonable agreement with the current results.

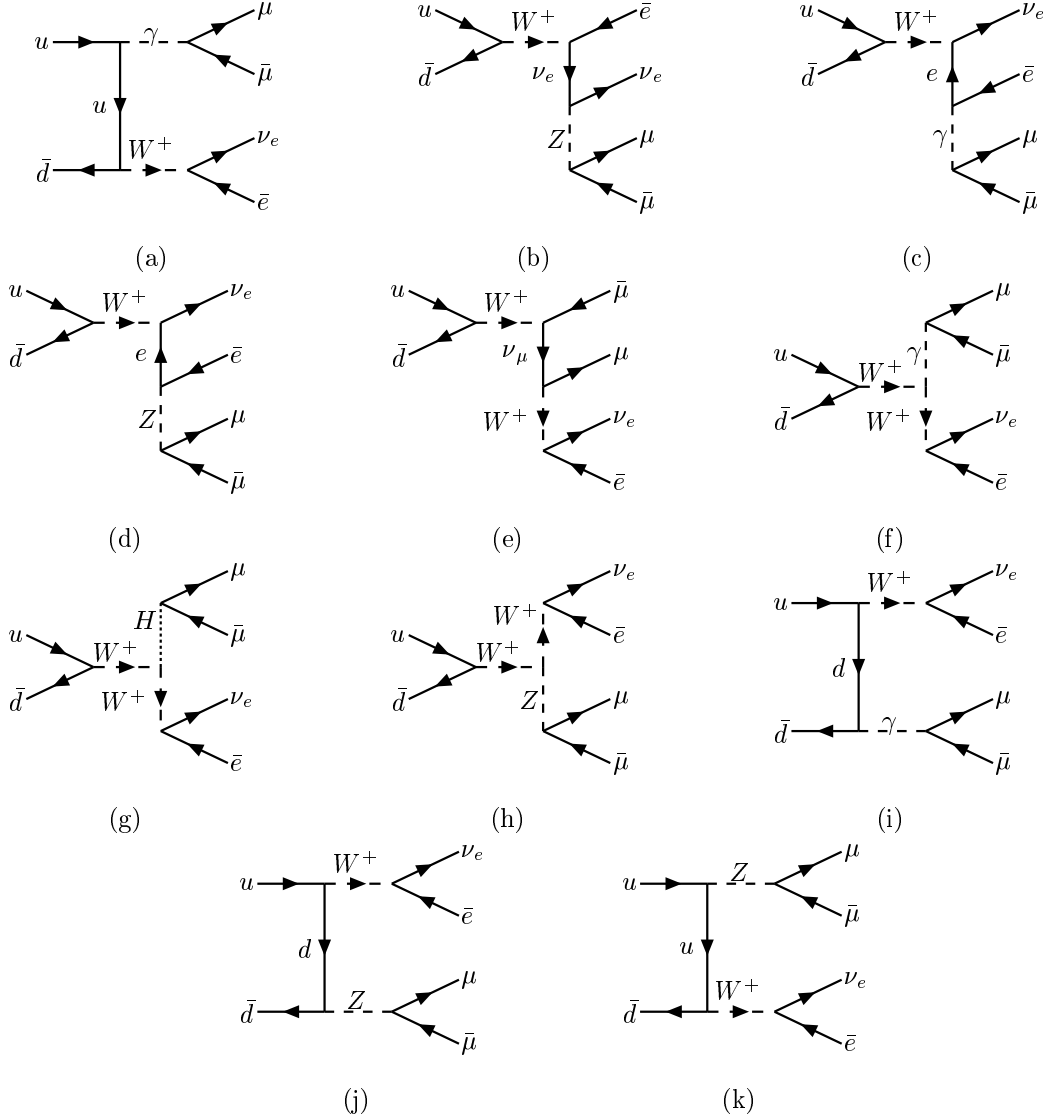


Figure 1: The diagrams for the $p\bar{p} \rightarrow W^+(Z/\gamma^*) \rightarrow \ell'^+ \bar{\nu}_{\ell'} \ell^+ \ell^-$ background. Here u and d stand for a generic up-type and down-type quark, respectively.

is larger than all previously considered backgrounds combined (2.1 fb [8]). This new source of background dwarfs previous estimates. For example, it is over 4 times the *total* background found in Ref. [6], and our total background is now more than 8 times the total background reported in [6].

These recent developments necessitate the invention of new cuts, specifically designed to suppress the off-shell Z/γ component of the background. One obvious variable to consider

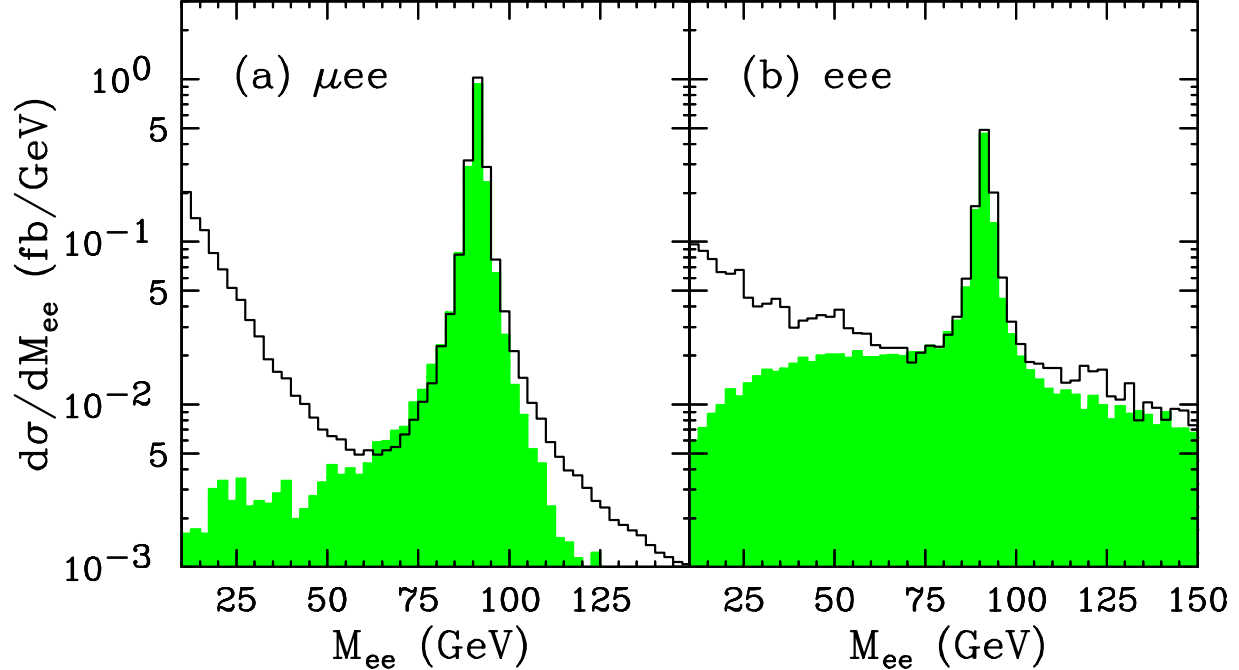


Figure 2: The invariant mass distribution $m_{\ell+\ell^-}$ of the opposite sign, same flavor leptons in (a) $\mu^\pm e^+ e^-$ events and (b) $e^\pm e^+ e^-$ events. The histograms show the results from COMPHEP and from PYTHIA (shaded). We have imposed nominal charged lepton cuts $p_T(\ell) > 5$ GeV and $m_{\ell+\ell^-} > 10$ GeV. Each histogram is normalized to its cross section. In (b), we fill both invariant mass combinations, each with weight 1/2.

is the invariant mass $m_{\ell+\ell^-}$ of an opposite sign, same flavor lepton pair in the event. The inclusion of the off-shell photon contribution increases the relative weight of events with low $m_{\ell+\ell^-}$. In anticipation of this effect, in Ref. [8] we employed a low invariant mass cut of $m_{\ell+\ell^-} > 12$ GeV.

In Fig. 2 we show the $m_{\ell+\ell^-}$ distribution in WZ events from COMPHEP and PYTHIA, before detector simulation and without ISR/FSR[‡]. We divide the WZ trilepton sample into opposite flavor (OF) ($e^\pm \mu^+ \mu^-$ and $\mu^\pm e^+ e^-$) and same flavor (SF) ($\mu^\pm \mu^+ \mu^-$ and $e^\pm e^+ e^-$) subsets, and show the results for each subset separately in Fig. 2a and Fig. 2b, respectively. For the OF sample, we know unambiguously which two leptons came from the off-shell Z/γ , so we enter one invariant mass combination per event. However, in the SF sample, there are

[‡]In ISAJET the invariant mass distribution of the leptons is a δ function at the Z -mass.

two possible invariant mass combinations for each event, and there is no way to know which one was from the Z/γ . Hence, in Fig. 2b we enter both combinations, each with weight 1/2.

First we see that neglecting the virtual photon contribution and the $Z-\gamma$ interference leads to a significant underestimate of the WZ background. In fact, the virtual photon contribution diverges in the limit $m_{\ell^+\ell^-} \rightarrow 0$! Second, the low-end invariant mass cut $m_{\ell^+\ell^-} > 12$ GeV that we used in [8] is clearly not very efficient in suppressing the additional γ^* background and the cut threshold needs to be increased. The optimum threshold will depend on the signal distribution, whose shape is controlled by the value of the chargino mass $m_{\tilde{\chi}_1^+}$ and is thus parameter space dependent. We therefore incorporate the low-end invariant mass cut into our optimization scheme, and we consider the cuts $m_{\ell^+\ell^-}^\gamma > \{10-60\}$ GeV, in 5 GeV increments. We choose the optimal one at each point in SUSY parameter space (for further details on our optimization procedure, see [8]).

In Fig. 3 we compare the COMPHEP and PYTHIA p_T distributions of the leptons. We see that most of the additional events due to the γ^* contribution tend to have small p_T . This implies that the soft cuts on the lepton p_T introduced in Ref. [6] may be inefficient in removing the new background component. The soft p_T cuts could be detrimental to the reach in regions of parameter space where the size of the background is important.

Alternatively, Ref. [9] suggests a cut on the transverse mass m_T of any $\ell\nu$ pair which may originate from a W -boson. The advantage of this cut is that it removes background events irrespective of whether the remaining lepton pair came from a Z , γ^* or the interference contribution. We shall therefore optionally incorporate this cut in our analysis of all three channels: $60 < m_T(\ell, \nu) < 85$ GeV. The remaining cuts that we use are fully described in Ref. [8] and will not be repeated here.

We present our results for the Tevatron reach in the trilepton, like-sign dilepton and dilepton plus tau jet channels in Figs. 4, 5, and 6, respectively. We require the observation of at least 5 signal events, and present our results as 3σ exclusion contours in the $M_0 - M_{1/2}$ plane, for two representative values of $\tan\beta$, 5 and 35. We fix $\mu > 0$ and $A_0 = 0$. The cross-

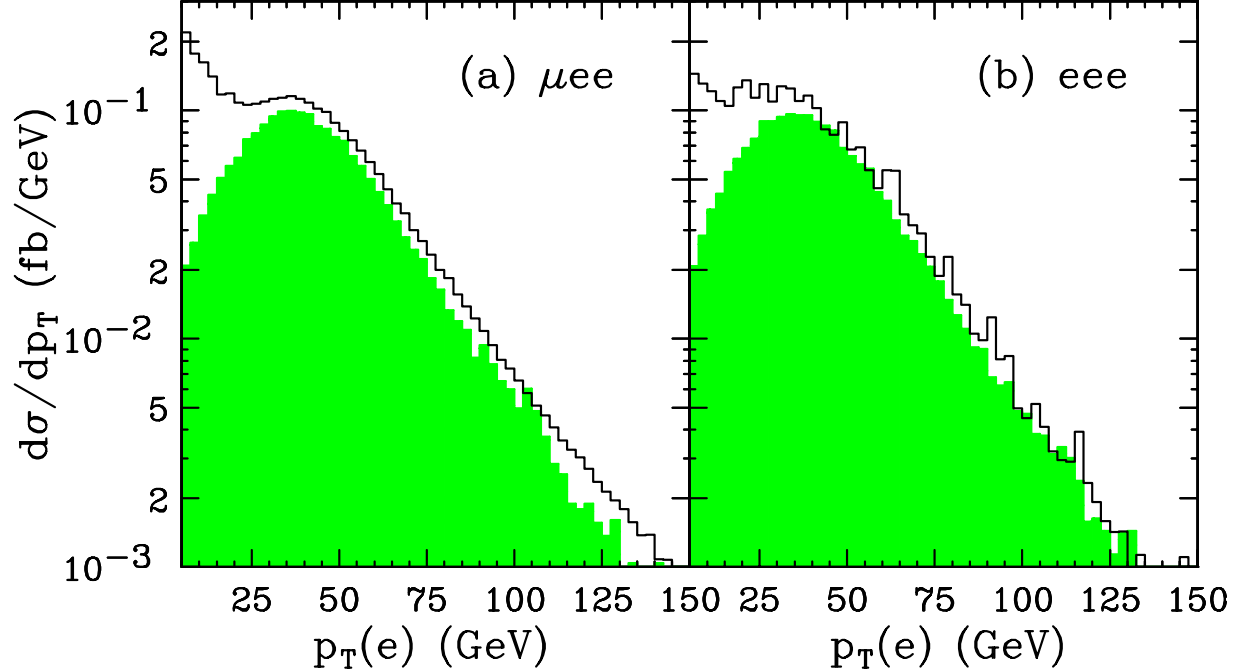


Figure 3: The same as Fig. 2, but for the p_T distribution of the leptons possibly coming from the Z . In the case of $\mu^\pm e^+ e^-$, we fill the p_T of both e^+ and e^- , each with weight 1/2. For the case of $e^\pm e^+ e^-$ we fill the p_T of the odd-sign lepton with weight 1/2 and the p_T of the like sign leptons with weight 1/4 each.

hatched region is excluded by current limits on the superpartner masses. The dot-dashed lines correspond to the projected LEP-II reach for the chargino and the lightest Higgs masses. In Figs. (a) the left dotted line shows where $m_{\tilde{\nu}_\tau} = m_{\tilde{\chi}_1^\pm}$ and the right dotted line indicates $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^\pm}$ (and $m_{\tilde{\tau}} \simeq m_{\tilde{\mu}} \simeq m_{\tilde{e}}$). In Figs. (b) the dotted lines show where $m_{\tilde{e}_R} = m_{\tilde{\chi}_1^\pm}$ (left) and $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^\pm}$ (right).

We see that although the inclusion of the γ^* background leads to a significant increase in the raw background cross section, the reach is somewhat similar to what was presented in Ref. [8], since the additional cuts help to increase the signal-to-noise ratio reasonably close to previous levels. At small $\tan\beta$ the trilepton channel provides for significant reach at both small M_0 ($M_0 \lesssim 150$ GeV) and large M_0 ($M_0 \gtrsim 400$ GeV). The other channels have somewhat less reach. At large $\tan\beta$ the dilepton + τ jet channel provides the best reach at small M_0 ($M_0 \lesssim 160$ GeV), while at large M_0 ($M_0 \gtrsim 400$ GeV) the trilepton channel still provides for

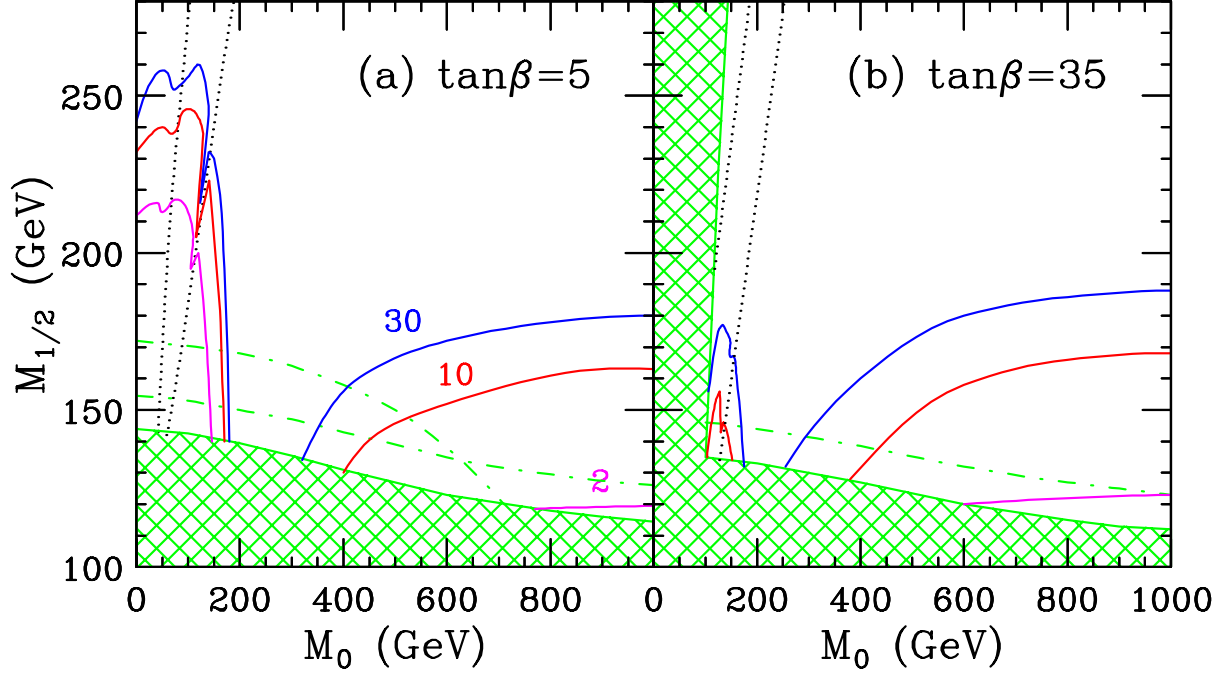


Figure 4: Tevatron reach in the trilepton channel in the $M_0 - M_{1/2}$ plane, for fixed values of $A_0 = 0$, $\mu > 0$ and (a) $\tan \beta = 5$, or (b) $\tan \beta = 35$. Results are shown for 2, 10 and 30 fb^{-1} total integrated luminosity.

decent reach with 30 fb^{-1} . With only 2 fb^{-1} the reach is quite limited.

In Fig. 7 (8) we show the optimum cuts chosen in our optimization procedure, in the M_0 , $M_{1/2}$ plane, for $\tan \beta = 5$ ($\tan \beta = 35$), in the small M_0 region. We use the following notation to describe the set of cuts at each point. The central symbol indicates the set of lepton p_T cuts: the symbols “1” through “5” refer to $\{11, 5, 5\}$, $\{11, 7, 5\}$, $\{11, 7, 7\}$, $\{11, 11, 11\}$ and $\{20, 15, 10\}$ GeV lepton p_T cuts, respectively. The left superscript shows the value (in GeV) of the low-end invariant mass cut ($m_{\ell^+\ell^-}^\gamma > 10$ to 60 GeV). A left subscript “T” indicates that the cut on the transverse $\ell\nu$ mass was selected. The right superscript shows the \cancel{E}_T cut: $\cancel{E}_T > \{15, 20, 25\}$ GeV (“15”, “20”, “25”), or no cut (no symbol). A right subscript denotes the high-end dilepton invariant mass cut: $|m_{\ell^+\ell^-} - M_Z| > \{10, 15\}$ GeV (“10”, “15”) or $m_{\ell^+\ell^-} < \{50, 60, 70, 80\}$ GeV (“50”, “60”, “70”, “80”). And finally, a tilde over the central symbol indicates that the luminosity limit came from requiring 5 signal events rather than 3σ exclusion.

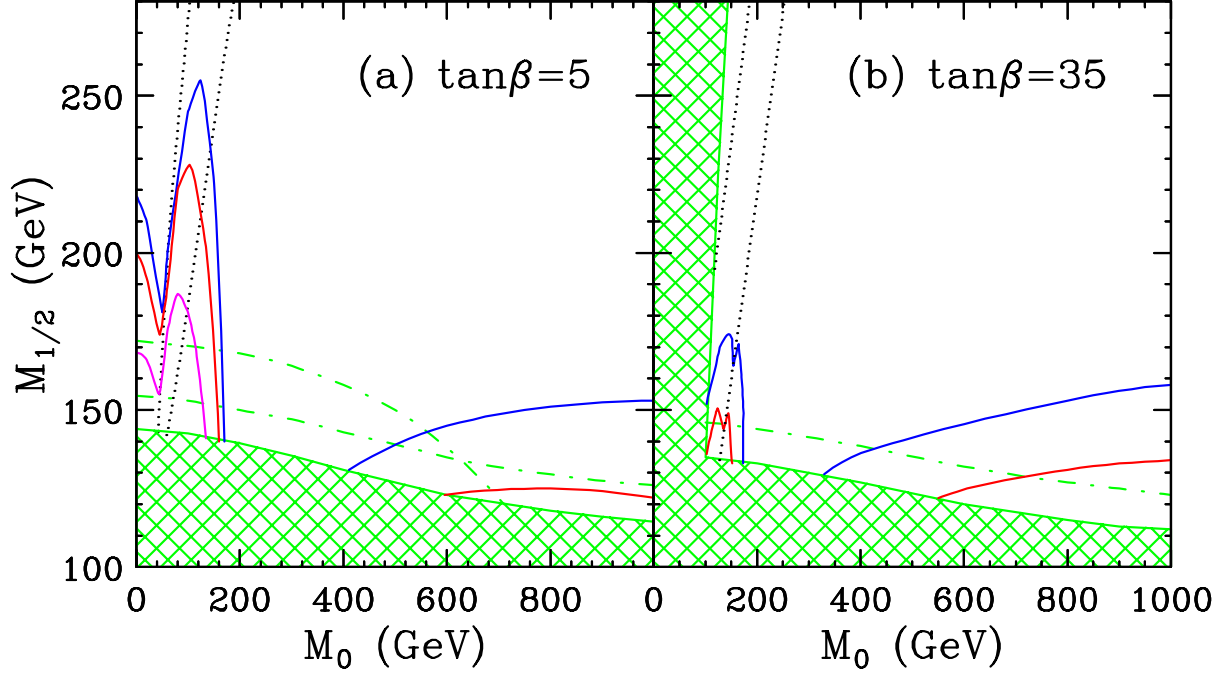


Figure 5: The same as Fig. 4, but for the like-sign dilepton channel.

In Fig. 7 we see that in the regions where background is an issue, the combination of the m_T cut and a tighter low-end dilepton mass cut $m_{\ell^+\ell^-}^\gamma \sim 20$ GeV is typically preferred. Indeed, we find that these additional cuts reduce the WZ background by more than a factor of 3, from 4.1 fb (with soft cuts [6]) to 1.2 fb. Notice, however, in the small $\tan\beta$ case the transverse mass cut is never enough by itself, i.e. whenever it is chosen, it is almost always supplemented with a $m_{\ell^+\ell^-}^\gamma$ cut of 15 to 25 GeV (with the exception of two points with high lepton p_T cuts). On the other hand, there are significant regions where the low invariant mass cut $m_{\ell^+\ell^-}^\gamma$ by itself is enough to kill the background, and the transverse mass cut is not needed. In the large $\tan\beta$ case the transverse mass is always chosen at small M_0 , but only occasionally at large M_0 .

We should point out that the optimum cuts in Figs. 7 and 8 can be interpreted in two ways. First, for a given total integrated luminosity, say 10 fb^{-1} , one can first roughly look up from Fig. 4 the sensitivity reach of the Tevatron. Then, for the parameter space well inside the sensitivity region, the actual choice of cuts is not so crucial. However, as one approaches

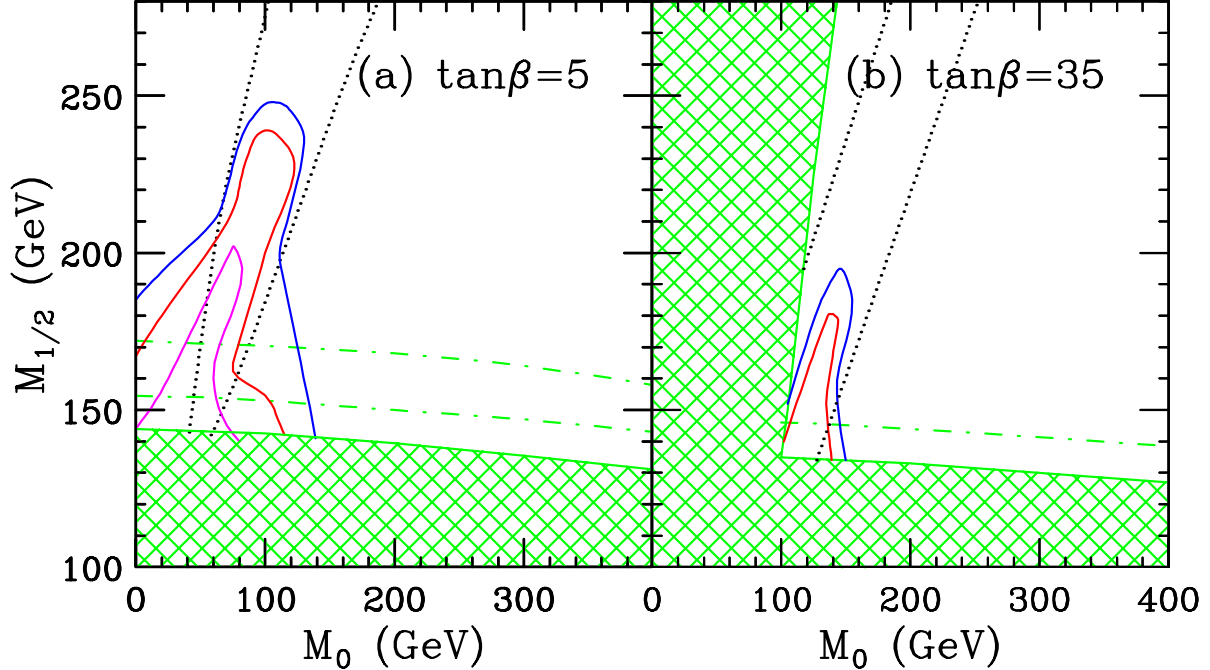


Figure 6: The same as Fig. 4, but for the dilepton plus a tau jet channel.

the boundary of the sensitivity region, the choice of optimum cuts as a function of parameter space (as opposed to a fixed, non-optimized set of cuts) can enhance the reach by an additional 10-20 GeV along the $M_{1/2}$ direction [8]. Alternatively, at a given parameter space point near the border, optimization can reduce the total integrated luminosity required to observe or exclude that point by up to a factor of two [8].

In conclusion, we find that the trilepton channel remains one of the leading candidates for SUSY discovery at the Tevatron. The other two channels are in a sense complementary, although not as powerful. The dilepton plus tau jet channel can be combined straightforwardly with the trilepton channel to maximally increase the reach. With the new very important $W\gamma^*$ background included, the reach of course suffers somewhat. We find that with only the standard Run 2 luminosity of 2 fb^{-1} the reach is quite limited. With the larger background it is even more imperative that the Tevatron collect as much luminosity as possible to have a decent chance at discovering supersymmetry.

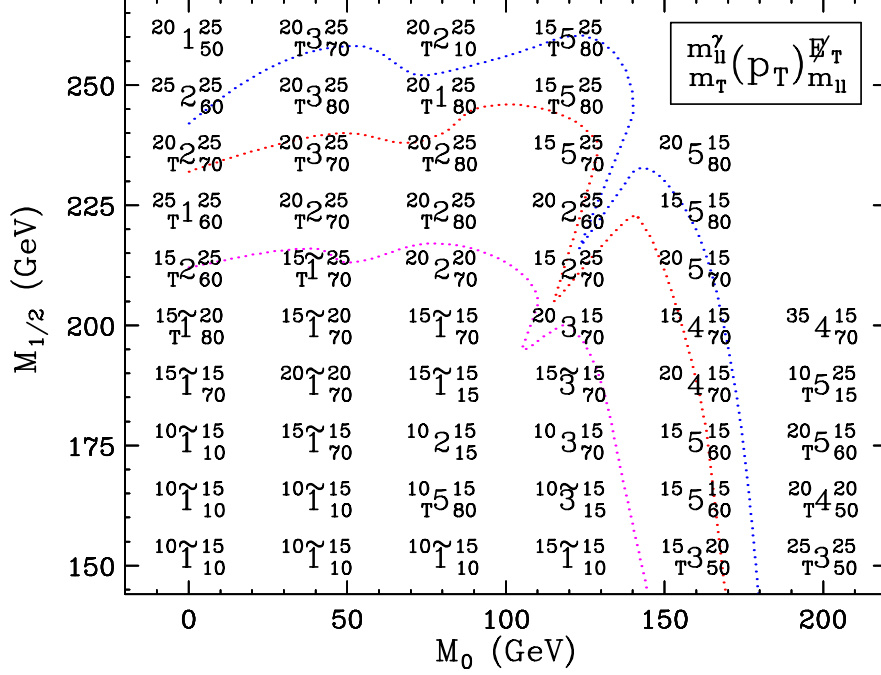


Figure 7: The optimal sets of trilepton cuts in the M_0 , $M_{1/2}$ plane, for $\tan\beta = 5$ and small M_0 . We show the optimal low end dilepton mass cut $m_{\ell\ell}^\gamma$, missing E_T cut \cancel{E}_T , high end dilepton mass cut $m_{\ell\ell}$, transverse $\ell\nu$ mass cut and lepton p_T cut (see text). The dotted lines indicate the reach contours from Fig. 4.

Acknowledgments

We thank J. Campbell, R.K. Ellis, J. Lykken, F. Paige and X. Tata for useful discussions and H. Baer for correspondence. K.T.M. (D.M.P.) is supported by Department of Energy contract DE-AC02-76CH03000 (DE-AC02-98CH10886).

Note added: Our results shown in Figs. 4-6 are similar to those of Ref. [9] once the error in the original version of [9] was fixed [22]. We warn the reader that the analysis of [9] still neglects the γ^* contribution and the interference effects in ZZ production, and lacks a detailed detector simulation for the WZ process.

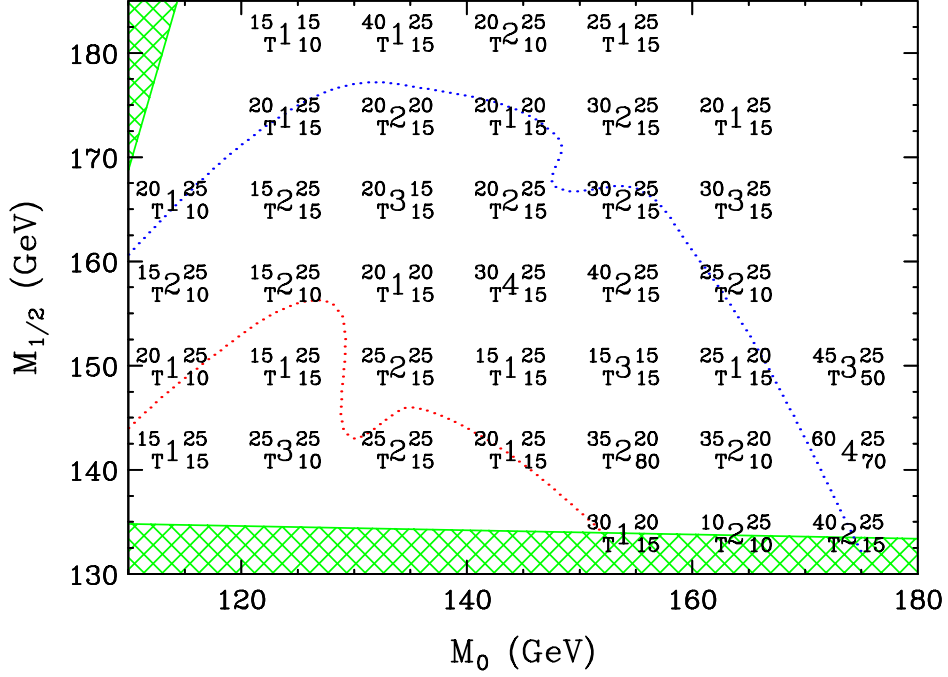


Figure 8: The same as Fig. 7, but for $\tan \beta = 35$.

References

- [1] Report of the SUSY/Higgs Workshop in preparation for Run II at the Fermilab Tevatron, to appear; some preliminary results at <http://fnth37.fnal.gov/susy.html>.
- [2] See, e.g. H. P. Nilles, Phys. Rep. **110**, 1 (1984), and references therein.
- [3] D. Dicus, S. Nandi and X. Tata, Phys. Lett. **B129**, 451 (1983);
A. Chamseddine, P. Nath and R. Arnowitt, Phys. Lett. **B129**, 445 (1983);
J. M. Frere and G. L. Kane, Nucl. Phys. **B223**, 331 (1983);
H. Baer and X. Tata, Phys. Lett. **B155**, 278 (1985);
H. Baer, K. Hagiwara and X. Tata, Phys. Rev. Lett. **57**, 294 (1986); Phys. Rev. **D35**, 1598 (1987);
R. Arnowitt and P. Nath, Mod. Phys. Lett. **A2**, 331 (1987).
- [4] R. Barbieri, F. Caravaglios, M. Frigeni and M. Mangano, Nucl. Phys. **B367**, 28 (1993);

- H. Baer and X. Tata, Phys. Rev. **D47**, 2739 (1993);
- H. Baer, C. Kao and X. Tata, Phys. Rev. **D48**, 5175 (1993);
- J. Lopez, D. Nanopoulos, X. Wang and A. Zichichi, Phys. Rev. **D48**, 2062 (1993);
- Phys. Rev. **D52**, 142 (1995);
- J. Lopez, D. Nanopoulos, G. Park, X. Wang and A. Zichichi, Phys. Rev. **D50**, 2164 (1994);
- J. Wells, in "International Workshop on Supersymmetry and Unification of Fundamental Interactions" (SUSY'94), Proceedings, Ann Arbor, Michigan, ed. by C. Kolda and J. Wells, (University of Michigan Press, Ann Arbor, 1994), p. 553;
- T. Kamon, J. Lopez, P. McIntyre and J. White, Phys. Rev. **D50**, 5676 (1994), [hep-ph/9406248](#);
- H. Baer, J. Gunion, C. Kao and H. Pois, Phys. Rev. **D51**, 2159 (1995), [hep-ph/9406374](#);
- H. Baer, C.-H. Chen, C. Kao and X. Tata, Phys. Rev. **D52**, 1565 (1995), [hep-ph/9504234](#);
- H. Baer, C.-H. Chen, M. Drees, F. Paige and X. Tata, Phys. Rev. Lett. **79**, 986 (1997), [hep-ph/9704457](#);
- H. Baer, C.-H. Chen, M. Drees, F. Paige and X. Tata, Phys. Rev. **D58**, 075008 (1998), [hep-ph/9802441](#).
- [5] S. Mrenna, G. Kane, G. Kribs and J. Wells, Phys. Rev. **D53**, 1168 (1996), [hep-ph/9505245](#).
- [6] V. Barger, C. Kao and T.-J. Li, Phys. Lett. **B433**, 328 (1998), [hep-ph/9804451](#);
- V. Barger and C. Kao, preprint FERMILAB-PUB-98/342-T, [hep-ph/9811489](#).
- [7] J. Lykken and K. Matchev, preprint FERMILAB-PUB-99/034-T, [hep-ph/9903238](#).
- [8] K. Matchev and D. Pierce, preprint FERMILAB-PUB-99/078-T, to appear in **Phys. Rev. D**, [hep-ph/9904282](#).
- [9] H. Baer, M. Drees, F. Paige, P. Quintana and X. Tata, [hep-ph/9906233](#).

- [10] S. Abachi *et al.*, Phys. Rev. Lett. **76**, 2228 (1996), [hep-ex/9512004](#);
 F. Abe *et al.*, Phys. Rev. Lett. **76**, 4307 (1996), [hep-ex/9603001](#);
 B. Abbott *et al.*, Phys. Rev. Lett. **80**, 1591 (1998), [hep-ex/9705015](#);
 F. Abe *et al.*, Phys. Rev. Lett. **80**, 5275 (1998), [hep-ex/9803015](#).
- [11] J. Nachtman, D. Saltzberg and M. Worcester, [hep-ex/9902010](#).
- [12] F. Paige, S. Protopopescu, H. Baer and X. Tata, preprint BNL-HET-98-39, [hep-ph/9810440](#).
- [13] T. Sjöstrand, Comp. Phys. Comm. **82**, 74 (1994),
 S. Mrenna, Comp. Phys. Comm. **101**, 232 (1997).
- [14] J. M. Campbell and R. K. Ellis, preprint FERMILAB-PUB-99/146-T, [hep-ph/9905386](#).
- [15] MADGRAPH, by T. Stelzer and W. Long, Comp. Phys. Comm. **81**, 357 (1994);
 HELAS, by H. Murayama, I. Watanabe and K. Hagiwara, preprint KEK-91-11 1992.
- [16] P. A. Baikov *et al.*, “*Physical results by means of CompHEP*”, in Proc. of the X Workshop on High Energy Physics and Quantum Field Theory (QFTHEP-95), ed. by B. Levchenko and V. Savrin, Moscow, 1996, p. 101, [hep-ph/9701412](#);
 E. Boos, M. Dubinin, V. Ilyin, A. Pukhov and V. Savrin, [hep-ph/9503280](#).
- [17] J. Conway, talk given at the SUSY/Higgs Workshop meeting, Fermilab, May 14-16, 1998.
 See also www.physics.rutgers.edu/jconway/soft/shw/shw.html.
- [18] S. Jadach, J.H. Kuhn and Z. Was, Comp. Phys. Comm. **64**, 275 (1990), *ibid.* **76**, 361 (1993).
- [19] L. Garren, STDHEP manual, <http://www-pat.fnal.gov/stdhep.html>.
- [20] K. Matchev, talk given at the Theory Group Seminar, April 22 1999, Fermilab, transparencies available at <http://www-theory.fnal.gov/people/matchev/matchev.html>;

D. Pierce, talks given at SLAC, May 7, 1999; UC Davis, May 11, 1999 and UC Santa Cruz, May 13, 1999.

[21] H. Lai *et al.*, Phys. Rev. **D55**, 1280 (1997).

[22] X. Tata, talk given at the SUSY '99 conference, Fermilab, June 14-19, 1999.